THE RETRIEVAL AND VALIDATION OF CLOUD PARAMETERS DERIVED FROM GOME-1 DATA

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ABSTRACT

Cloud top heights (CTHs) as derived by using measurements of two instruments (GOME and ATSR-2) onboard the ESA ERS-2 space platform are intercompared. It was found that cloud altitudes obtained using thermal IR measurements of ATSR-2 highly correlate with those obtained from top-of-atmosphere backscattered solar light measurements of GOME in O2 A-band using both the semi-analytical cloud retrieval algorithm SACURA and the neural network cloud retrieval algorithm ROCINN. The average cloud top heights as obtained by these diverse techniques differ by an average bias of -1.31 km and standard deviation of 0.84 km of SACURA applied to GOME data with respect to ATSR-2. The average bias and deviation of ROCINN are found to be 0.28 km and 1.55 km, respectively.

Key words: Clouds; Top Height; Remote Sensing; Oxygen A-band, Global Ozone Monitoring Experiment.

1. INTRODUCTION

Since clouds play an essential role in the Earth's climate system, it is important to understand their characteristics as well as their distribution on a global scale using satellite observations. Though the main scientific objective of GOME (Global Ozone Monitoring Experiment, [1]) is the retrieval of properties of trace constituents, its temporal and spatial coverages are also relevant for the study of cloud parameters. GOME is a space-borne spectrometer that flies on ERS-2 since April 1995 and measures reflected solar radiation in the wavelength range between 280 and 790 nm at moderate high spectral resolution of 0.2 to 0.4 nm (see Table 1).
Clouds affect the path a photon travels through the atmosphere and change, therefore, the interpretation of the depth of an absorption band. They act as reflectors and their infuence can be summarized in three components: firstly they shield the troposphere, hiding the gas columns below; secondly they enhance the absorption above, yielding an increased band depth; finally they cause multiple scattering, as photons travel inside.

Table 1. GOME instrument technical specifications.

Parameter	
Data availability	06/1995-today
	(No global coverage since 06/2003)
Spectral Coverage	240–790 nm
Spectral Resolution	0.2–0.4 nm
PMD Coverage	3 p-PMD 300–800 nm
Viewing geometry	nadir
Ground Pixel Size	320×40 km^2
Swath Width	960 km
Equator Crossing	10:30 AM Local Time

Hence the properties to be known are cloud albedo, optical thickness and top height.
The aim of this paper is to describe the retrieval scheme of such properties with SNGome (based on SACURA) and to compare the results for cloud top height with two different and independent algorithms. The first algorithm is GRAPE (Global Retrieval of ATSR Cloud Parameters and Evaluation), based on the IR thermal measurements of ATSR-2 and relying on the ORAC (Oxford and RAL - Rutherford Appleton Laboratory - Aerosols and Clouds) engine. The data are made freely available via the British Atmospheric Data Center (BADC - badc.nerc.ac.uk). The second algorithm is ROCINN, operationally deployed by DLR, based on the O_2 A-band technique and a neural network approach ([8]). The data are delivered "in bundle" with the GOME radiances.

2. RETRIEVAL ALGORITHMS

2.1. *O_2 A-band algorithms: SNGome and ROCINN*

It has been extensively proven that cloud top height can be retrieved from measurements in the oxygen A-band (758–778 nm) ([2, 7, 17]). As a matter of fact, when a cloud is idealised as a perfect reflector, every photon

striking the cloud top will be scattered back and will not be absorbed by the oxygen underlying the cloud. So the depth of the absorption line decreases as the cloud altitude increases (Fig. 1).

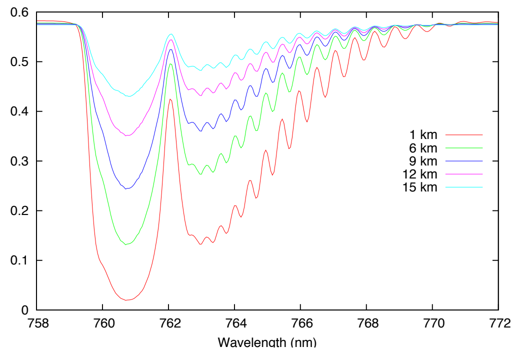

Figure 1. Synthetic top-of-atmosphere cloud reflectances for different heights. Parameters: cloud geometrical thickness 1 km, cloud optical thickness 10, solar zenith angle 60°, nadir view, effective radius 6 μm, gamma PSD.

Due to its large footprint, the GOME retrieval deals with broken cloud fields. In order to reduce a partially cloudy case to a completely cloud covered scene the independent pixel approximation (IPA, [10]) is employed, *i.e.*, the measured reflectance R_{mes} is written as a linear combination

$$R_{mes} = c_f R_{cl} + (1 - c_f) R_s \tag{1}$$

where c_f and R_s stand for cloud fraction and surface albedo, respectively. The value of c_f is delivered by DLR, calculated with the OCRA algorithm and it is based on the analysis of the GOME PMD measurements ([9]). The ancillary value of R_s is taken from the TEMIS project ([3]), *i.e.*, a global database of minimum Lambertian reflectivities, derived from 5.5 years of GOME observations. The retrieval of cloud properties can now be accomplished ingesting R_{cl} in SACURA, developed at Bremen University ([6, 14]). The optimal estimation approach of the algorithm compares R_{cl} with forward cloud reflectances, calculated within the framework of the asymptotic theory. This model parametrises the TOA (Top-Of-Atmosphere) reflectance, taking into account as aerosol and multiple scattering as well as surface contribution (whereas ROCINN models clouds as Lambertian reflectors). For the detailed description and the complete set of equations see [4, 5]. The spectral dependence of the TOA cloud reflectance in the O_2 A-band is used for the CTH determination, whereas the line outside absorption band ($\lambda = 758$ nm) allows the retrieval of the cloud albedo and optical thickness (a technique used also in [11]). We used the following constraints in SNGome: the cloud geometrical thickness must be in the range 0.8–10 km, the cloud lower boundary must be larger than the surface height, the cloud top height must be smaller than 17 km (14 km for ROCINN). The retrieved values of CTH are given with respect to the ground surface height.

The error analisys has been carried out with forward synthetic reflectances (simulated with SCIATRAN 3.1, [13]) for different COTs and CTHs (see Fig. 2). The average error is comprised within ±0.2 km, unless for thin high clouds, where it rises up to 1.2 km. For the simulations, a single-layered homogeneous water cloud of geometrical and optical thickness of 1 km and 10 respectively, a gamma particle distribution of mean radius 6 μm , solar zenith angle of 60°, nadir view and a black underlying surface have been assumed.

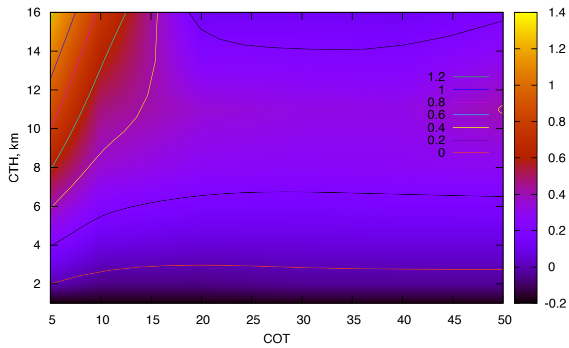

Figure 2. Absolute error (in km) in the CTH retrieval with SNGome as function of CTH and COT.

2.2. IR retrieval algorithm: GRAPE

ATSR-2 and GOME retrievals of CTHs are based on different physical principles. In particular, cloud brightness temperature as measured by ATSR-2 at two IR channels available, *e.g.*, 10.8 and 12 μm, can be related to the cloud top height because colder clouds are generally located at higher altitudes in the troposphere. Therefore, the minimum temperature at which the local temperature profile matches the derived cloud top temperature is assumed to equal the cloud top height. This is the basic idea behind the IR retrieval. Furthermore, the main assumptions in the retrieval scheme are as follows:

1. LookUp Tables (LUTs) of atmospheric transmittance and reflectance (DISORT as radiative transfer code and MODTRAN for the gaseous absorption part).
2. Lambertian surface (MODIS albedo product for 2002 over land).
3. Cloud model as single layered.
4. Pressure, temperature and H_2O profiles according to ECMWF.
5. Data are down-sampled to create a grid of 4 pixels along and 3 pixels across track.

The detailed theoretical description of the algorithm as well as a validation report are in preparation [12, 16].

3. MEASUREMENTS AND COMPARISON

For the intercomparison, four months (January, April, July, October 1999) have been chosen in order to give a representative range of atmospheric conditions. The selected co-located pixels must satisfy the following conditions:

- The cloud optical thickness is larger than 5 and smaller than 100.
- The solar zenith angle is smaller than 75°.
- The latitudes are comprised between 50°N and 50°S.
- Cloud fraction equals one (fully cloudy pixels).

The values for ATSR-2 cloud top altitudes (in km) are calculated from top pressures (in mbar) with the following equation

$$Z^* = 16\, log_{10}\left(\frac{1000}{P}\right).$$

According to the GRAPE Product Description Document (v.3.2), only ATSR-2 pixels (3×4 km^2) with moderate (in order to increase spatial coverage) and high quality flag are taken into account within a GOME nadir pixel (320×40 km^2), counted and averaged. In Fig. 3 and Fig. 4 the correlation and distribution of the deviations are shown. Whereas a relatively high correlation of 0.83 has been found, the peak centered at the negative deviation of -1 km likely arises due to the cloud fraction used in the IPA (described in the previous section). Due to the great footprint size of GOME, errors in the cloud cover propagate into the retrieved CTHs through biased reflectances. An overestimation in cloud cover reduces the cloud reflectance R_{cl} in Eq. 1, which, in turn, results in a lower cloud top height. The difference between OCRA cloud fraction, used in SNGome, and GRAPE cloud fraction is plotted in Fig. 6, for a value range of 0.7–1. Further work is ongoing to ascertain this effect. The comprehensive seasonal statistical data are summarised in Table 2.

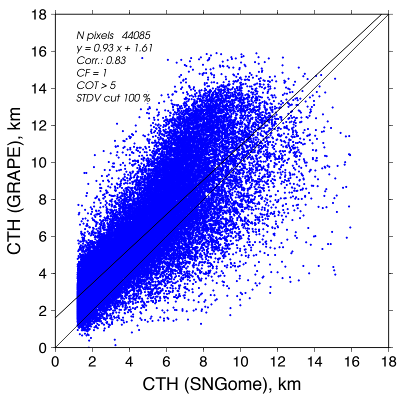

Figure 3. Correlation plot between CTHs obtained using SNGome and GRAPE.

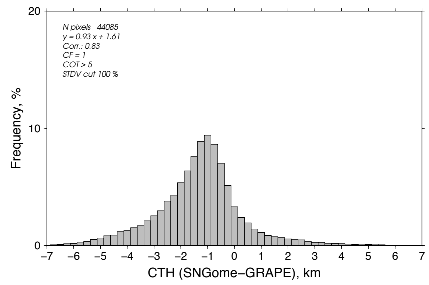

Figure 4. Distribution of biases of SNGome-derived CTHs as compared with GRAPE.

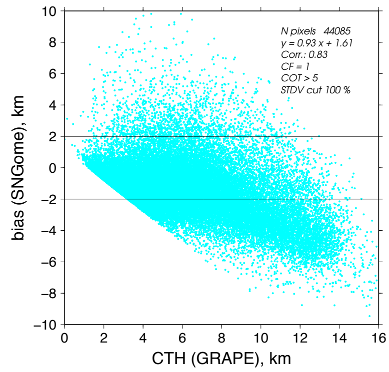

Figure 5. Dependence of SNGome bias B_G on GRAPE CTH.

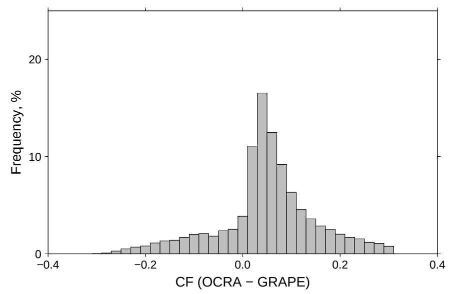

Figure 6. Frequency histogram of differences between OCRA-DLR and GRAPE cloud fraction.

Furthermore, to investigate the negative shift of SNGome, the bias is plotted as a function of CTHs retrieved by GRAPE in Fig.5. The negative biases larger than 2 km correspond to large values of ATSR-2-derived CTHs. This finding confirms that GOME nadir measurements are less sensitive to thin cirrus clouds, which are easily detected by the thermal IR ATSR-2 measurements. As a matter of fact, the O_2 A-band samples larger atmospheric volumes compared to IR techniques, which give informations from the tops of upper clouds.

The same analysis has been carried out for ROCINN, on the same dataset (see Figs. 7 – 10 and Table 3). ROCINN correlates well with SNGome (0.89) and GRAPE (0.92),

Table 2. Seasonal statistical data. Brackets mean average values. H stands for cloud-top-height (km) , B for bias (km) of SNGome (subscript S) w.r.t. GRAPE (G). σ stands for standard deviation.

Month Number of GOME pixels	Jan. 10782	Apr. 11996	Jul. 10232	Oct. 11075	Total 44085
$< H_S >$	4.45	4.36	4.88	4.06	4.43
$< H_G >$	5.67	5.71	6.15	5.44	5.74
$< B_{SG} >$	-1.22	-1.35	-1.27	-1.39	-1.31
σ_{SG}	0.88	0.85	0.85	0.77	0.84

nevertheless yielding higher CTHs in both cases. The causes are currently under investigation.

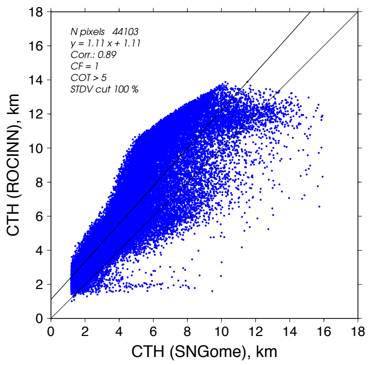

Figure 7. Correlation plot between CTHs obtained using SNGome and ROCINN.

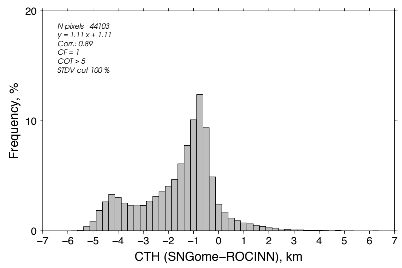

Figure 8. Distribution of biases of SNGome-derived CTHs as compared with ROCINN.

4. CONCLUSIONS

On the whole, the average difference between CTH derived from GOME data using SACURA with respect to ATSR-2 GRAPE is -1.31 ± 0.06 km with standard deviation of 0.84 km. The average difference between ROCINN compared to SNGome is 1.59 ± 0.12 km with

Table 3. Monthly statistical data. Brackets mean average values. H stands for cloud-top-height (km) , B for bias (km) of ROCINN (subscript R) w.r.t. SNGome (S) and ROCINN (R) w.r.t. GRAPE (G). σ stands for standard deviation.

Month Number of GOME pixels	Jan. 10787	Apr. 12007	Jul. 10233	Oct. 11076	Total 44103
$< H_R >$	5.78	6.08	6.47	5.75	6.01
$< H_G >$	5.67	5.71	6.15	5.44	5.74
$< H_S >$	4.45	4.36	4.88	4.06	4.43
$< B_{RG} >$	0.11	0.38	0.31	0.31	0.28
$< B_{RS} >$	-1.33	-1.72	-1.58	-1.70	-1.59
σ_{RG}	1.39	1.61	1.73	1.48	1.55
σ_{RS}	0.89	1.21	1.18	1.09	1.09

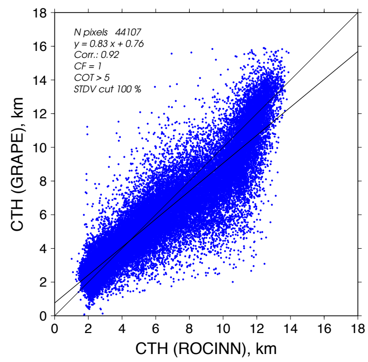

Figure 9. Correlation plot between CTHs obtained using ROCINN and GRAPE.

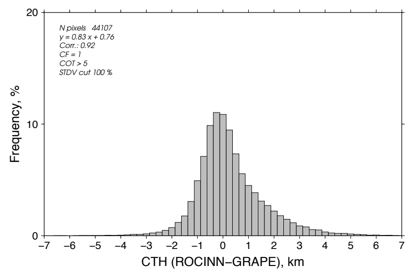

Figure 10. Distribution of biases of ROCINN-derived CTHs as compared with GRAPE.

a standard deviation of 1.09 km. In all cases SNGome underestimates cloud altitudes.

The comparison between ROCINN and ATSR-2 GRAPE shows an average difference of 0.28 ± 0.08 km and a standard deviation of 1.55 km.

The findings evidenced in this paper partially confirm the previous study in [15], in which just 4 orbits of ERS-2 were analysed. Beside the aforenamed cloud cover error, due to the use of OCRA, a possible reason for the discrepancy between SNGome and GRAPE can be found in

the different CTH retrieval, as applied to ATSR-2.
The SACURA retrieval can be further improved using cloud fraction values derived from GRAPE, even if this step results in a decreased spatial coverage, due to the limited across nadir swath ($\approx$ 500 km) of the ATSR-2 instrument.

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REFERENCES

[1] Burrows, J., Weber, M., Buchwitz, M., Rozanov, V., Weissenmayer, A. L., Richter, A., DeBeek, R., Hoogen, R., Bramstedt, K., Eichmann, K. U., Eisinger, M., and Perner, D. (1999). The Global Ozone Monitoring Experiment (GOME): Mission Concept and First Scientific Results. *J. Atmos. Sci.*, 56:151–175.

[2] Fischer, J. and Grassl, H. (1991). Detection of cloud-top height from reflected radiances within the oxygen a band, part 1: Theoretical studies. *J. Appl. Meteorol.*, 30:1245–1259.

[3] Koelemeijer, R., de Haan, J., and Stammes, P. (2003). A database of spectral surface reflectivity in the range 335-772 nm derived from 5.5 years of GOME observations. *J. Geophys. Res.*, 108:4070.

[4] Kokhanovsky, A. (2006). *Cloud Optics*. Springer, Dordrecht.

[5] Kokhanovsky, A. and Nauss, T. (2006). Reflection and transmission of solar light by clouds: asymptotic theory. *Atm. Chem. Phys.*, 6:5537–5545.

[6] Kokhanovsky, A., Rozanov, V., Zege, E. P., Bovensmann, H., and Burrows, J. (2003). A semianalytical cloud retrieval algorithm using backscattered radiation in 0.4–2.4 μm spectral region. *J. Geophys. Res.*, 108:4008.

[7] Kuze, A. and Chance, K. V. (1994). Analysis of cloud top height and cloud coverage from satellites using the O_2 A and B bands. *J. Geophys. Res.*, 99:14481–14491.

[8] Loyola, D. (2004). Automatic cloud analysis from polar-orbiting satellites using neural network and data fusion techniques. In *IEEE International Geoscience and Remote Sensing Symposium*, volume 4, pages 2530–2534.

[9] Loyola, D. and Ruppert, T. (1998). A new PMD cloud-recognition algorithm for GOME. *ESA Earth Observation Quarterly*, 58:45–47.

[10] Marshak, A., Davis, A., Wiscombe, W., and Titov, G. (1995). The verisimilitude of the Independent Pixel Approximation used in cloud remote sensing. *Remote Sens. Environ.*, 52(1):72–78.

[11] Nakajima, T. and King, M. D. (1990). Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. part I: Theory. *J. Atmos. Sci.*, 47(15):1878–1893.

[12] Poulsen, C., Sayer, A., Campmany, E., Dean, S., Ewen, G., Arnold, C., Thomas, G. E., Grainger, R. G., Siddans, R., Lawrence, B., and Watts, P. (2010). The GRAPE cloud retrieval algorithm. Technical report, EODG, Oxford, England.

[13] Rozanov, A., Rozanov, V., Buchwitz, M., Kokhanovsky, A., and Burrows, J. (2005). SCIATRAN 2.0 - a new radiative transfer model for geophysical applications in the 175–2400 nm spectral region. *Adv. Space Res.*, 36(5):1015–1019.

[14] Rozanov, V. and Kokhanovsky, A. (2004). Semianalytical cloud retrieval algorithm as applied to the cloud top altitude and the cloud geometrical thickness determination from top-of-atmosphere reflectance measurements in the oxygen A band. *J. Geophys. Res.*, 109:4070.

[15] Rozanov, V., Kokhanovsky, A., Loyola, D., Siddans, R., Latter, B., Stevens, A., and Burrows, J. (2006). Intercomparison of cloud top altitudes as derived using GOME and ATSR-2 instruments onboard ERS-2. *Remote Sens. Environ.*, 102:186–193.

[16] Sayer, A., Campmany, E., Dean, S., Ewen, G., Poulsen, C., Arnold, C., Thomas, G. E., Grainger, R. G., Siddans, R., Lawrence, B., and Watts, P. (2010). Evaluation of GRAPE cloud products. Technical report, EODG, Oxford, England.

[17] Yamamoto, G. and Wark, D. (1961). Discussion of letter by A. Hanel: Determination of cloud altitude from a satellite. *J. Geophys. Res.*, 66(5):3596.